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Publication Date

2007-08-22

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RESEARCH REPORT
UCB-ITS-TSRC-RR-2007-4

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August 22, 2007

Biofuel Boundaries:
Estimating the Medium-Term Supply Potential of Domestic Biofuels

Andrew Jones, Michael O'Hare, Alexander Farrell

A UC Berkeley Transportation Sustainability Research Center
Working Paper

updated
August 22, 2007

Abstract

We estimate the physical supply potential of biofuels from domestic municipal solid waste, forestry residues, crops residues and energy crops grown on existing cropland using optimistic assumptions about near-term conversion technologies. It is technically feasible to produce a significant amount of liquid biofuel (equivalent to 30-100% of 2003 gasoline demand) without reducing domestically produced food and fiber crops or reducing the total calories available as domestic animal feed. Most of this supply can be attributed to the potential of energy crops, with the combination of municipal solid waste and forestry residues supplying between 10% and 30% of recent gasoline demand.

Our modeling approach to energy crops is unique in that it explicitly models interactions between the feed and fuel system using an optimization procedure that adjusts cropland allocation among major crops subject to a simple food security constraint. Our modeling indicates that sizable increases in biofuel production need not result in decreased availability of food or animal feed, but *will* require changes in the composition of livestock diets away from hay and soymeal toward either whole corn or feed coproducts of biofuel processing such as distillers grains. Whole corn yields very high levels of digestible calories per land area, so shifting away from soymeal and hay to corn feed permits the same total level of digestible calories to be produced from a smaller area. Furthermore, the coproduction of animal feeds with biofuels relaxes the need to grow dedicated feed crops at all. Thus, under our food security constraint, energy crops which yield feed coproducts (such as corn ethanol) can be grown on a larger area than other energy crops, potentially yielding higher total levels of biofuel than other crops (such as switchgrass) that yield more biofuel but less animal feed per land area. When the food security constraint is lifted nearly 200% of recent gasoline demand could be met by liquid biofuels, corresponding to a scenario in which all current cropland is converted to high-yielding switchgrass.

The size of our supply estimates indicate that while domestic biofuels can play a large role in transportation, achieving such high levels of ethanol production may not be socially or ecologically desirable, or may be extremely costly with costs expressed through higher food prices, biodiversity loss, water degradation, and soil erosion. Policies designed to protect natural resources and stabilize food prices should be implemented early in order to achieve a reasonable level of biofuel production that avoids pushing these boundaries.

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Abbreviations Used

MSW	Municipal Solid Waste
CRP	Conservation Reserve Program
DGS	Distillers Grains with Solubles
DOE	Department of Energy
USDA	United States Department of Agriculture

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Introduction

As a distributed source of liquid transportation fuels, biomass may play an important role in achieving medium-term energy security goals in the US. Furthermore, liquid biofuels can be produced so that their life-cycle greenhouse gas emissions are significantly lower than those of conventional transportation fuels, offering the possibility of reduced climate effects from the transportation sector. However, liquid biofuels are unlikely to be a "silver bullet" for solving our energy security and climate change problems because of supply limitations. Just how much of a role biofuels can play in meeting these twin objectives depends on several constraints.

A rational policy approach to biofuels will recognize these constraints and package biofuel incentives with a portfolio of policies aimed at reducing the overall demand for transportation fuels via vehicle efficiency and smart growth as well as policies promoting other low carbon distributed fuels such as electricity. In addition, variation in biofuel production practices warrants policies that address the life-cycle impacts of biofuels on food security, global climate, regional climate, soil, air, water, and biodiversity. Biofuel policies may also need to distinguish among biofuels according to their life-cycle liquid fuel consumption in order to maximize energy security benefits. However, relatively little gasoline and diesel are typically used in the production of biofuels (6). Thus the *net* supply of liquid fuels – the final product less the liquid fuels used to make the product – often approaches the *gross* supply of liquid biofuels.

Physical constraints on biofuel supply include the availability of feedstocks and the efficiency of converting feedstocks into fuels. For example, agriculture-derived feedstocks are constrained by land, water, and nutrient resources as well as limitations on the efficiency of photosynthesis. Many processes for converting biomass into liquid fuels involve external energy inputs, such as electricity, process heat, or hydrogen in addition to the biomass itself. For any given process, there is a maximum fraction of all input energies that can be preserved in the final fuel.

The cost of producing biofuels also limits supply. In well-functioning markets, resources that are difficult to access or have valuable alternative uses will not be developed to their full physical potential. However, markets for both energy and agriculture are severely distorted by subsidies, mandates, and tariffs (10) Furthermore, these markets do not value several important social and environmental externalities associated with biofuels. For instance, some biofuels may be undervalued for their ability to mitigate global climate change, whereas the alternative use of biomass for food may be undervalued to the extent that poor people cannot afford to pay for what is actually of infinite value, their own subsistence. Furthermore, the price of biomass generally does not reflect the unpriced costs of energy cropping on soil, water, biodiversity, and climate. While such costs are the beyond the scope of the present analysis, they are vital considerations. Developing biofuels within the bounds of ecological and human health will require governance mechanisms to impose new constraints that present markets fail to impose.

In this study, we put considerations of cost and practicality aside to estimate the "outer-limits" physical supply potential of biofuels from US domestic resources using existing or near-term technologies. The magnitude of this potential is of policy significance as an upper bound on biofuels' contribution to global warming (or petroleum displacement) goals. We do this by examining data on various biomass resources and conversion processes, and for the case of energy crops, by developing scenarios of new crop distributions.

In most of our scenarios, we impose one external constraint – that the total amount of food, and animal feed for domestic consumption, remains constant. We chose to consider this constraint and not others because of its analytical tractability and high value to society.[1] However, for completeness, we do present two scenarios in which food and feed production are completely displaced by energy crops. In principle, an economy can forgo food production entirely and trade for it, as long as the rest of the world is willing to increase production enough; for example, Singapore, a city-state with trivial amounts of agricultural land, imports all its food and enjoys a very high standard of living. For the United states to move significantly from being a food exporter to being an importer of even a large fraction of its food would be a barely imaginable earthquake on the world trade scene and impossible given domestic U.S. politics, but we model this case on the "upper bound" principle.

The ecological constraints mentioned above are serious considerations for a world with high levels of biofuel development (particularly from energy crops) and should not be taken lightly. We discuss such constraints qualitatively throughout the text. Similarly, the internalized costs of procuring diffuse resources and processing low-quality resources are considered only qualitatively in this study. We do not consider direct logging of existing forests for bioenergy feedstock. Due to the ecological sensitivity of such an endeavor, we believe that more advanced scenario modeling would be required to evaluate tradeoffs among competing uses and values of forestland. We do consider forest industry wastes and residues as discussed below.

We chose to focus on domestic resources because of the political imperative to develop such resources for energy security and economic development purposes. Although US energy security and climate benefits can be accomplished via imported biofuels, domestic biofuels have two important strategic advantages. First, domestic resources are unlikely to suffer from supply disruptions due to geo-political events, and second the greenhouse gas impacts of domestic biofuel production can be readily monitored and regulated. On the other hand, it may be the case that imported biofuels can be produced with more greenhouse gas efficient production pathways, or that the magnitude and stability of international supply may be of interest from an energy security perspective. These issues are not addressed here.

In the following sections, we first discuss the methodology used to estimate feedstock availability and potential fuel supply from wastes and primary resources. Crop scenarios and land use assumptions are discussed in this section. We then discuss conversion technologies. Results are presented in the same order as methodology with wastes followed by primary resources. The paper concludes with a short discussion and an appendix on conversion technologies and fuels.

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[1] Note the crudeness of this analytical approach to food security. First, this approach does not recognize the likely increase in food prices induced by competition for agricultural resources by fuel crops. Second, it is conceivable that food security be met with less domestic production of food and animal feed, particularly with a dietary shift away from grain-fed meat and dairy to more resource efficient consumption, or through secure trade arrangements.

Methods

The goal of this study is to describe the envelope of upper bounds on resource availability, deliberately extending the analysis into a range of tiny probabilities of occurrence. We consider several categories of potential biomass feedstocks that have been discussed in the literature on biofuels. For each supply category, we provide a low and high estimate. This range is driven by uncertainty in biomass feedstock availability rather than uncertainty in conversion yields. The biofuel yield per unit of feedstock used is the highest value for any well-documented conversion technology available in the near-term (5-10 years). See appendix A for an overview of biomass feedstocks and conversion pathways, including near and long-term technologies. All of the calculations were performed in a simple spreadsheet designed to allow the easy manipulation of key assumptions such as conversion and crop yields with clear documentation of primary data sources[2].

Feedstocks Considered

Two kinds of biofuel feedstocks are considered in this study: waste streams and primary resources.

Wastes

Waste streams, such as municipal solid waste and logging industry residues, are byproducts of existing activities. Their development for ethanol may improve the economics of engaging in those activities, but those activities are not likely to increase dramatically in order to supply ethanol feedstocks. Thus the present study estimates the supply potential of waste feedstocks by simply examining current industry trends. It should be noted that waste streams are not necessarily "free" in the sense of having no opportunity cost. Logging residues may play an important role in soil retention and wildlife habitat if left in the forest. Similarly, a significant amount of municipal solid waste is currently diverted from landfills for recycling, composting, or combustion for energy.

Our low estimate of waste feedstock supply excludes wastes currently used for other economic purposes, whereas the high estimate assumes that the entire wastestream is used for biofuel production. Thus, in the high estimate calculations, we implicitly assume that price mechanisms favor biofuel development over alternative uses without violating our definition of waste (i.e. that economic use of the feedstock does not encourage further feedstock production).

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[2] Please contact the author for access to this spreadsheet. It is our hope that it can easily be adapted to incorporate new scenarios and better data as the relevant industries evolve.

Municipal Solid Waste (MSW)

Municipal solid waste (MSW) typically refers to the mixture of wastes collected in municipal areas that is sent to municipal landfills, incinerators, or recycling facilities (2). It generally does not include industrial process wastes, hazardous waste, construction and demolition debris, automobile waste, sewage sludge or agricultural wastes, some of which are disposed of in municipal landfills. We address the potential using construction and demolition debris and some agricultural wastes elsewhere in this report.

Barriers to biofuel generation from MSW include the ability to effectively separate cellulosic material from other wastes, potential variation in feedstock quality and availability, as well as the cost of handling and drying very moist materials and competing uses for MSW such as recycling, compost, and landfill gas generation. The use of MSW for biofuel -- when economically practical -- has very few drawbacks and even has the positive effect of reducing demand for landfill space. However, MSW is a noxious material and potentially hazardous, making the siting of production facilities challenging. From a climate perspective, fuel derived from MSW will likely have low life-cycle greenhouse gas emissions because upstream emissions – those involved in generation of the feedstock – would have been generated regardless of the use of MSW. On the other hand, the alternative fate of carbon in landfills matters too. If landfilled MSW is sequestered, its diversion to biofuel production represents a gain of carbon in the atmosphere, whereas if landfilled MSW leads to the release of methane, its diversion may represent a decrease in climate forcing because methane is more potent as a greenhouse gas than carbon dioxide.

We considered two studies of MSW generation in the US, which represent a range of uncertainty about actual MSW generation rates (2, 21). The first report that we considered is from the EPA and is based on a mass balance methodology[3] (2). This report estimates that 246 million tons of MSW were generated in 2005. The methodology in this report also permits categorizing the waste stream in terms of product source and material. Of the 246 million tons generated in 2005, 160 million tons were potential cellulosic biofuel feedstocks in the form of paper and paperboard, yard trimmings, food waste, wood, and other organics. However, some of this material (64 million tons) was recovered for recycling and compost. After waste recovery, 95 million tons of potential cellulosic feedstock was landfilled or burned (2). Plastics and textiles are also potential feedstocks for fuels derived through non-enzymatic conversion pathways, such as gasification. However, the current study considers only the enzymatic pathway as discussed in the methods section and so plastics are not considered.

The second report that we considered used surveys to obtain information directly from each state about MSW generation, recycling, combustion, and landfilling (21). Different states use different methods to track MSW including direct sampling of the wastestream, thus the accuracy of the report depends upon the accuracy of individual state data. The report aggregated data from each state, adjusting for inconsistencies in the definition of MSW. This report estimated that MSW generation in 2004 was 388 million tons, nearly 60% higher than the EPA report.

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[3] This method applies adjustment factors that have been developed by the EPA to data on products imported, exported, and produced to estimate the generation of different types of MSW.

However, the survey methodology did not permit categorizing the material composition of MSW.

Rather than attempt to assess the accuracy of either of these two reports, we accept their variation as an uncertainty range on the availability of MSW. Because the second report does not consider the material composition of MSW, we apply the relative fraction of MSW composition from the first study to the second

Forestry Residues

The forest products industry generates residues and wastes at every level of production from logging to the disposal of construction debris. We considered several categories of such materials, as estimated by the USDA Forest Service in the DOE Billion Ton Vision (18). These include logging residues - the upper portions of trees currently left behind when an area is logged, forest products industrial residues - such as black liquor and sawdust, and construction and demolition debris. We also considered the potential availability of forest thinnings, which are small diameter trees and undergrowth removed from managed forests in order to reduce the risk of catastrophic fire. The presence of such material is a major problem in many forests due to historically misguided management. The current cost of thinning forests is often prohibitive, and use of thinned material for biofuel conversion may improve the economics of fire management.

Each of the resources listed above may have significant costs associated with their use as biofuel feedstocks. Logging residues play an important ecological role in preventing soil erosion, nutrient cycling and providing wildlife habitat, in addition to being a diffuse resource that may require specialized equipment to harvest and collect for biofuel conversion. Forest industry residues such as black liquor are mostly (93%) (18) already used to generate energy on-site in facilities such as paper mills. Diversion of these resources to biofuel production will require substituting natural gas, electricity, or even coal to provide industrial process energy. Construction and demolition debris, like MSW may vary in quality and may be costly to collect to a central facility. Finally, forest thinnings are very diffuse and costly to collect.

In the *Billion Ton Vision* report, USDA provides an estimate of additional residues that might become available as the forest products industry expands and becomes more efficient. This estimate includes residues from each of the categories discussed above and is based on a technical assessment of the US forestry industry from 1952-2050 (8). We take this projection to be speculative and so include it only in our high estimate of feedstock availability.

Primary Resources

Primary resources, such as land and water, can be used to produce energy crops for biofuel production. The potential supply of biofuels from primary resources is more complicated to estimate than the supply from wastes. This is because the feedstock supply itself can’t be taken as a fixed complement of existing activities, but results from the re-allocation of resources away from current uses. For example, the existing corn crop has been partially diverted away from feed and export use toward ethanol production and more land has been brought into corn production, increasing the total amount of corn and reducing the supply of soy and other crops. Alternatively high-yielding switchgrass could be grown as a cellulosic ethanol feedstock instead of existing crops, but processing switchgrass into ethanol does not create the animal feed coproduct that corn ethanol does, nor does it have the option value of being sold in grain markets if the ethanol market is unstable. We do not attempt to weigh these tradeoffs here. Rather, we explore the technical limits within which markets and policy can shape outcomes.

Crop residues occupy a grey area between waste stream and primary resource. This is because the ability to collect and use crop residues for biofuels may actually influence the development of certain crops over others. For instance, the ability to collect and sell corn stover, the stalks and leaves of the corn plant, as a biofuel feedstock may bias the production of corn over switchgrass. In this study crop residues are treated in conjunction with energy crops and represent an increase in the effective biofuel yield per unit of land area from corn and other crops.

Energy Crops and Crop Residues

Agricultural lands supply food for domestic consumption, large quantities of animal feed, fiber for textiles, and export commodities. Figure 1 shows the current allocation of US cropland to major crops. Grassland pasture and range, which is typically so dry and unproductive of biomass that its only economic use is for foraging animals, is included for reference. While the possibility to grow bioenergy crops on rangeland and pastureland does exist, this study only considers crops grown on prime cropland (including conservation reserve program land). This is because yield data for corn and switchgrass, the two model energy crops considered are based on assumptions of adequate soil and water resources.

Of the 440 million acres of land classified as cropland by the USDA, approximately 60 million acres is used for cropland pasture, and 40 million acres is classified as idle cropland, which includes the Conservation Reserve Program (CRP) lands[4]. Of the remaining 340 million acres, 260 million acres are dedicated to four major crops: soybeans (74 million acres), corn (74 million acres), hay (62 million acres), and wheat (50 million acres). The remaining 80 million acres are used to grow cotton, sorghum, small grains, oilseeds, fruits, vegetables, nuts, and tobacco. All fruits vegetables and nuts are grown on just 8 million acres. (1)

Approximately 210 million acres (47%) of cropland is used to produce animal feed or used for cropland pasture (see Figure 1) (1), that is, for meat and milk. Cropland characterized as pasture may be marginal or degraded cropland not suitable for high yielding energy crop production. Thus, cropland pasture is excluded from the present analysis. This leaves 150 million acres (34%) of land used exclusively to produce crops for animal feed, mostly corn, soybeans, and

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[4] The CRP is a USDA's primary land retirement program which pays farmers to take environmentally sensitive land out of production. Many of these are productive cropland that happen to have highly erodable soils.

hay. When we refer to feed crops in the scenarios, we mean crops grown on these 150 million acres. Approximately 60 million acres (14%) of cropland is used to produce exports. This area is composed mostly of soy, corn, wheat, and cotton (1).

We estimate the potential role of energy crops and crop residues as biofuel feedstocks by developing several scenarios. Each scenario alters the existing allocation of cropland to include more bioenergy crops, assuming that no new land is brought into crop production and that the yields of various crops are constant across the land area currently used for crops. Thus existing pasture, rangeland, forest and other non-crop uses remain unchanged in each scenario, but the portion of cropland used for soy, hay, or other existing crops may be reduced to accommodate more energy crops.

We chose to examine two model energy crops: corn and switchgrass. Corn forms the basis of the existing biofuels industry and is likely to continue to play an important role for the foreseeable future. Producing ethanol from corn has the added benefit of yielding a protein-rich animal feed coproduct in the form of distillers grains (DGS) or similar products such as corn gluten meal. Because our analysis is focused on the near term, we assume a recent corn crop yield of 160 bushels per acre.

Additional biofuels can be produced from an acre of corn by harvesting the cellulosic residue known as corn stover, which we model in some of our scenarios. Because the removal of stover from corn fields negatively affects soil erosion and soil quality, considerable debate exists about the appropriate level of removal (13, 16). Consistent with the upper-bound approach, we assume that a high fraction (75%) of corn stover is harvested in those scenarios. In practice, acceptable removal rates will depend on regional yields, climatic conditions, and cultivation practices (23).

Switchgrass is a high-yielding native perennial grass that has received much attention as a prospective energy crop(15). Switchgrass and other herbaceous perennial crops are not necessarily associated with multiple uses and coproducts like corn. However, the potential yield per acre of dedicated energy crops such as switchgrass are higher than for corn and the perennial nature of the crop allows for the possibility of lower inputs, decreased soil erosion, and increased soil carbon accumulation compared to annual crops such as corn(11, 14). For these reasons, and because switchgrass can only be utilized as a biofuel feedstock using more advanced conversion technologies, the expected life-cycle greenhouse gas emissions associated with switchgrass ethanol are much lower than for corn (6). In our model, we assume that breeding and cultivation improvements will increase the current average switchgrass yield of 13.5 Mg/ha to the currently highest reported yields of 22 Mg/ha(15).

As a result of crop re-allocation, the amount of export, food, and animal feed production changes in our scenarios. All but two scenarios utilize a simple food security constraint that holds all cropland used for domestic food production constant and holds the amount of calories available for animal feed constant while a linear optimization algorithm maximizes biofuel production.

For instance, distillers grains, a protein-rich coproduct of corn ethanol production may comprise a larger fraction of animal feed diets in these scenarios, but the same or greater magnitude of digestible calories are available to livestock despite diversion of corn grain from the feed system. For simplicity, digestible calories are based on beef and dairy net energy values(4, 19) and expressed in tons of corn equivalent. Cattle are ruminants and can more easily utilize the energy in many feeds compared to swine and poultry, so our digestible calorie factors may be overestimates from the perspective of the average feed consuming unit. However, cattle consume a large portion of the feed currently consumed (9).

We did not consider the availability of protein as animal feed constraint. Ignoring protein availability is justifiable from the standpoint of converting existing feed corn into corn ethanol because the protein value of the corn is preserved in ethanol coproducts such as distillers grains. However, the conversion of soy acres to corn ethanol or switchgrass production may lead to a deficit in protein available as feed. This would be an interesting area in which to expand the detail of the model.

For most crops, determining the proportion of harvested land used for animal feed and exports was simple because the harvested portion of the crop is itself the commodity that is traded or used as feed (e.g. corn, cotton, hay) (1). However, soybeans are often separated into two different products – soymeal and soybean oil – which are not exported or used for feed in the same proportions. We chose to track the fate of the soymeal in determining whether a particular unit of soybeans was used for feed, exports, or other uses. Tracking the fate of soybean oil would underestimate the use of soy as animal feed. However, this choice partially undermines the food security constraint because scenarios in which soybean production declines may be associated with decreases in domestic soybean oil production.

The crop scenarios combine information from different time periods in order to use the most recent data available. For instance, data on gross allocation of land to cropland, rangeland, pasture, etc. was based on USDA's 2002 Census of Agriculture(12), which is not available for more recent years, whereas allocation of cropland to specific crops such as corn for grain, corn for ethanol, soybeans etc. is based on more recent data from 2004(1). We chose to use 2004 data to reflect recent trends in corn production related to the development of corn ethanol. In general, we used the most recent data available for a given parameter or we selected hypothetical assumptions about future conditions from the literature.

Crop yield assumptions were taken from a variety of sources and are summarized in Table 1 (1, 15, 16, 22). Figure 2 combines crop yield data with assumptions about biofuel conversion processes and animal feed values to illustrate the feed and fuel yields of selected crops in our model. Protein yields are included for reference, although they do not play an essential role in our model at this time. It should be noted that although high yielding switchgrass produces more fuel energy per unit of land than corn ethanol (even with stover collection), corn ethanol also produces animal feed coproducts. These tradeoffs are important drivers of the modeling results.

Table 1 Assumed Crop Yields

Crop yield assumptions were taken from a variety of sources as listed here.

Assumed Crop Yields		
	Dry Mg / Harvested Ha	**Source**
Corn Grain	10.1	NASS 2005 Ag Statistics(1)
Corn Stover (at 75% harvest rate)	7.5	Nelson et al 2004(16)
Soy Bean	2.9	NASS 2005 Ag Statistics(1)
Switchgrass (current average)	13.5	Argonne Lab GREET model(22)
Switchgrass (high yield)	22.0	Mclaughlin et al, 2005(15)

Crop Scenarios

We considered 4 corn ethanol scenarios and 2 switchgrass scenarios. Information about each scenario is summarized in Table 2 and discussed in more detail below. Two scenarios – C4 and S2 consider the extreme case in which all cropland is used to produce either corn or switchgrass for biofuel. The other scenarios employ a simple food security constraint which optimizes biofuel production on the land area permissible for biofuel production in each particular scenario while maintaining domestic food production (fruits, vegetables, nuts, as well as wheat, soy, and corn used directly for food or seed) fiber production (cotton for domestic use) and a constant level of feed calories for domestic livestock as discussed above.

Table 2 Crop Scenarios

We considered four corn scenarios and two switchgrass scenarios grown either on land currently used for feed crops, land currently used for feed and export crops, or on all cropland. High-yielding corn refers to corn with 75% stover collection and high-yielding switchgrass refers to the highest reported yields at this time. The final column refers to whether or not the food security constraint was applied as discussed in the text.

Corn Scenarios	Switchgrass Scenarios	Potential Land	Crop Yield	Food Constraint?
C1		Feed Crops	current	yes
C2		Feed and Export Crops	current	yes
C3	S1	Feed and Export Crops	high	yes
C4	S2	All Cropland	high	no

In scenario C1, we considered corn ethanol production on land currently used to produce domestic feed crops only. The corn yield is based on recent years, and the food security constraint applies.

Scenario C2 is like scenario C1, except that land used to produce exports is used to produce corn ethanol as well.

Scenario C3 considers the collection of corn stover for ethanol production in addition to the corn grain. This effectively results in a higher yield of ethanol per unit of land area dedicated to corn ethanol production, as well as an additional ethanol yield from corn grown for other purposes. The food security constraint still applies.

In scenario C4, the food security constraint is lifted and we compute the maximum physical potential of corn ethanol production with stover removal on all existing cropland using near term technologies.

Scenario S1 considers high yielding switchgrass on land currently used for feed and export crop production with a food security constraint.

Scenario S2 is like scenario C4 in that the food security constraint is lifted to compute the maximum technical potential of ethanol from switchgrass grown on all existing cropland.

Figure 1 Current Cropland and Rangeland Allocation

Of the 440 million acres of land classified as cropland by the USDA, approximately 60 million acres is used for cropland pasture, and 40 million acres is classified as idle cropland, which includes the Conservation Reserve Program (CRP) lands. Of the remaining 340 million acres, 260 million acres are dedicated to four major crops: soybeans (74 million acres), corn (74 million acres), hay (62 million acres), and wheat (50 million acres). Approximately 150 million acres is dedicated to crops grown for animal feed and an additional 50 million acres is for growing export commodities. In 2004, only 11 million acres were used for biofuel production. For comparison, 590 million acres are considered grassland pasture and range,

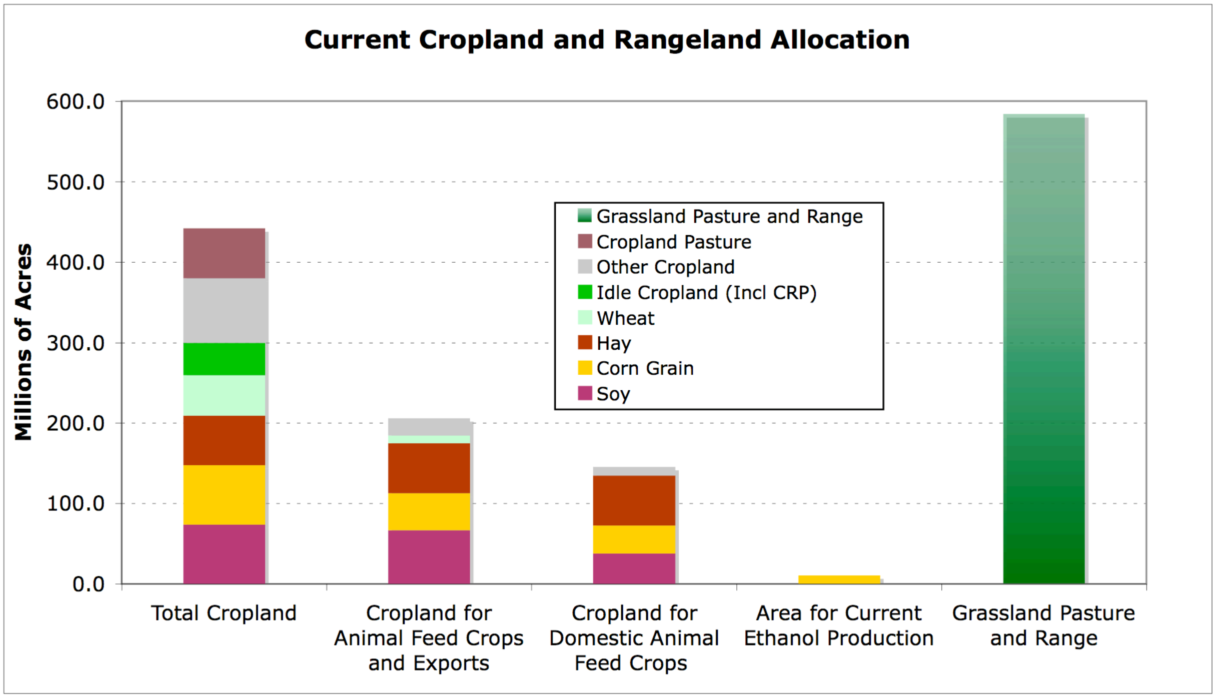
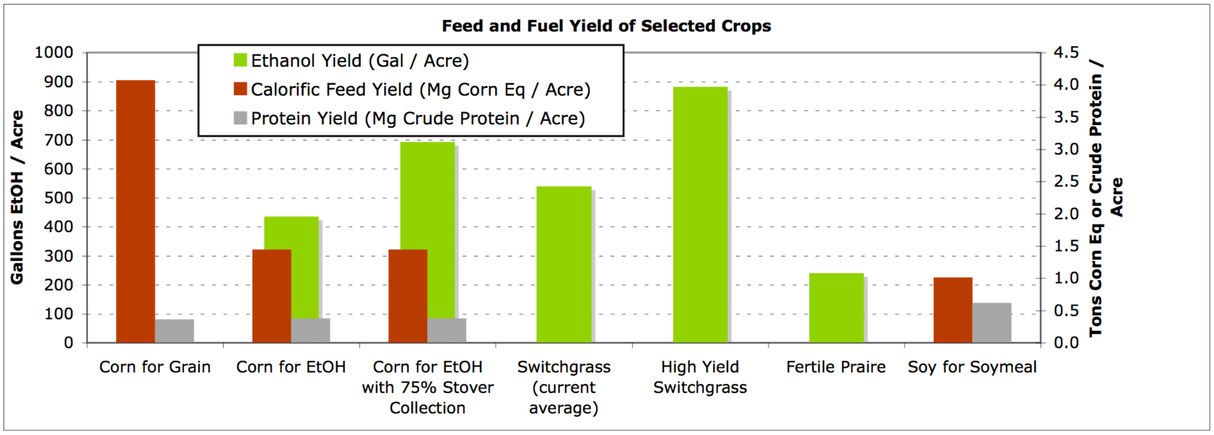


Figure 2 Feed and Fuel Yield of Selected Crops

According to our crop yield and process yield assumptions, corn grain yields high levels of animal feed calories per acre (expressed as tons of corn equivalent). About 1/3 of the feed calories and all of the crude protein in corn are available as distillers grains when corn is converted to ethanol, which is still more calories per acre than soybeans. Although high-yielding switchgrass produces more ethanol per acre than corn with high levels of stover collection, we do not assume that switchgrass produces a feed coproduct. Soybeans produce more protein per acre than corn. Prairie is included for reference, assuming aboveground biomass can be converted using cellulosic saccharification.



Biofuel Conversion Processes Considered

For each feedstock considered we chose the best-yielding near-term conversion process for which reasonable yield data was available. Consequently, two conversion processes were chosen from among the many possibilities outline in Appendix A: the conventional drymill starch-to-ethanol process widely used today and a cellulose-to-ethanol process.[5] The assumed yields per dry ton of feedstocks are given in Table 3.

The starch-to-ethanol process was applied to corn grain feedstocks and yield is based on the latest generation of drymills in use in 2005(22). The cellulose-to-ethanol process was applied to all other potential feedstocks with the exception of switchgrass and is based on the Department of Energy's Theoretical Ethanol Yield Calculator(3). This calculator provides a theoretical maximum yield given the composition of various sugars in the feedstock. According to the DOE, the expected practical yield is in the range of .6 to .9 times the theoretical maximal yield. In the spirit of creating upper-bound estimates, we chose a factor of .9 for all cellulosic yields. Thus variation in our final biofuel supply estimates reflects uncertainty in feedstock availability rather than process yields. Switchgrass cellulose-to-ethanol yields were based on the GREET model(22).

Because the DOE calculator is based on dry tons of feedstock, we were forced to make assumptions about moisture content of feedstocks in cases where this information was not available. Similarly, when information about the proportion of various sugars was not available, we matched unknown feedstocks with similar feedstocks for which sugar composition is well documented. Theoretical maximum ethanol yield varied from 82 gallons of ethanol per dry ton for forest thinnings to 116 gallons of ethanol per dry ton for mixed paper.

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[5] For some heterogeneous cellulosic feedstocks, such as MSW, the gasification to Fischer-Tropsch fuel pathway may turn out to be a more appropriate pathway due to its relative tolerance of feedstock variation. However, at this time, reliable yield data is not available because of the paucity of research on biomass gasification to FT-fuels compared to enzymatic cellulosic ethanol.

Table 3 Biofuel Yield Per Dry Ton of Feedstock

This table lists the conversion process, fuel produced (ethanol in all cases), and assumed yield for each feedstock considered in this study.

Feedstock	Conversion Process	Yield (GGE / Dry Ton)
MSW		
Paper and Paperboard	cellulosic saccharification	70
Wood		61
Food, Other Organic		70
Yard Trimmings		49
Forestry		
Logging Industry Residues	cellulosic saccharification	49
Fuel Treatments (Forest Thinnings)		49
Forest Products Industry Residues		61
Construction and Demolition Debris		61
Energy Crops		
Corn	dry mill fermentation	72
Switchgrass	cellulosic saccharification	67
Crop Residues		
Corn Stover	cellulosic saccharification	68

Results

Municipal Solid Waste

Figure 3 demonstrates the range of MSW generation estimates and relative breakdown of different materials. Brackets indicate the portion of the MSW stream that represents potential cellulosic ethanol feedstocks.

Our high estimate of MSW feedstock availability is based on the higher estimate of total MSW generation and assumes that all potential cellulosic feedstocks are used for cellulosic ethanol production, including feedstocks that are currently recycled or combusted for energy. The low estimate uses the lower estimate of total MSW and assumes that existing recycling and recovery program remain intact. These values are summarized in Table 4, along with our assumed moisture content for these feedstocks.

Based on the cellulosic ethanol assumptions discussed in the methods section, we estimated the technical potential of supplying ethanol from MSW. These results are presented in comparison to recent gasoline demand in Figure 4. At current rates of waste generation, MSW has the technical potential to supply between 2 and 9 percent of the 2003 US gasoline demand, mostly from paper and paperboard feedstocks. The cost of collecting and handling MSW feedstocks may be a significant cost barrier to developing this level of biofuels from MSW as discussed above. A significant fraction (about 50%) of current waste paper and paperboard is separated from the wastestream for recycling, so the infrastructure for this separation already exists. However, society must weigh the value of biofuel against the opportunity cost of not recycling these materials.

Figure 3 Municipal Solid Waste Generation and Recovery

There is a significant discrepancy in the literature regarding how much MSW is generated in the US (represented by the first two columns). Portions marked with brackets represent potential cellulosic feedstocks. The third column represents the amount of MSW that is not currently recycled, composted, or combusted for energy.

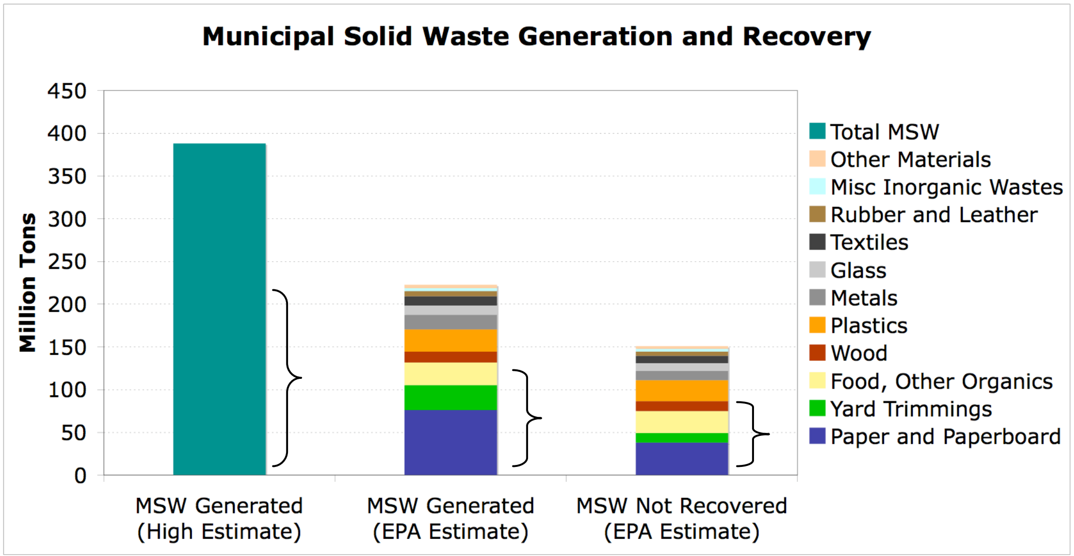


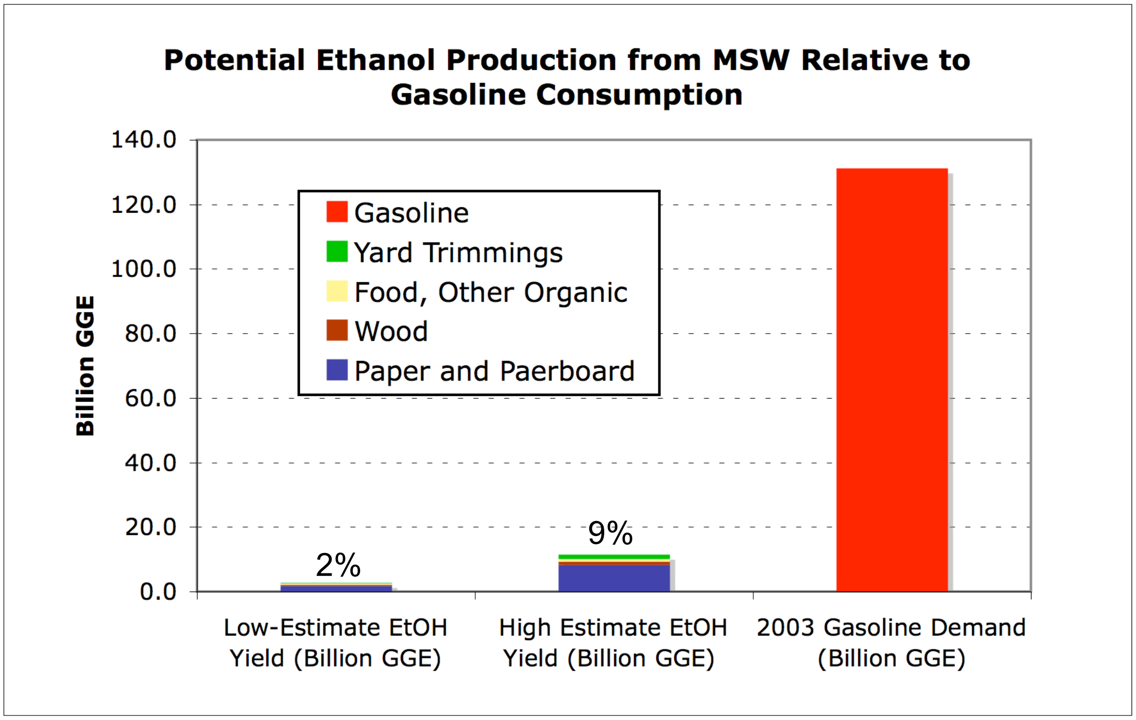
Table 4 Estimated Cellulosic Feedstocks from MSW

This table lists our assumptions about the availability of MSW feedstocks. The high and low estimates reflect variation in published studies of MSW generation. Furthermore, the low estimate excludes materials currently utilized for recycling, composting, and combustion.

	High Estimate (million tons)	Low Estimate (million tons)	Assumed Moisture Content
Paper and Paperboard	133	28	10%
Wood	22	10	25%
Food, Other Organic	46	22	75%
Yard Trimmings	51	7	50%
Total	**251**	**67**	

Figure 4 Potential Ethanol Production from MSW Relative to Gasoline Consumption

Biofuels derived from MSW have the technical potential to supply between 2% and 9% of recent gasoline demand. Most of this is from paper and paperboard, half of which is already recycled for non-energy uses.



Forestry Resources

The estimated yearly technical supply of forestry related wastes and residues is presented in Figure 5 and summarized in Table 5. The two differences between the high and low estimates are that the high estimate includes an estimate of additional residues from an expanded industry (as discussed in the methods section) and the low estimate excludes materials currently used for energy services. These feedstocks have the technical potential to supply 5 %to 14% of recent US gasoline demand. These results are presented in Figure 6.

Figure 5 Forestry Related Feedstocks for Bioenergy

Between 130 and 320 million tons of forestry related feedstocks are available or might become available for biofuel conversion. The high estimate includes an estimate of additional residues from an expanded industry (see methods) and the low estimate excludes materials currently used for energy.

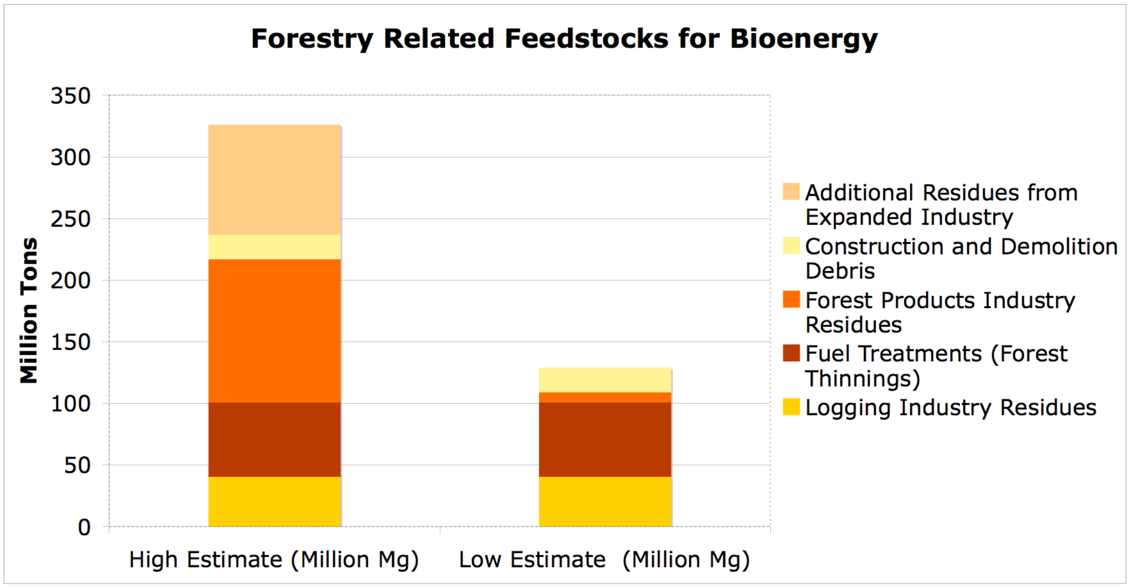


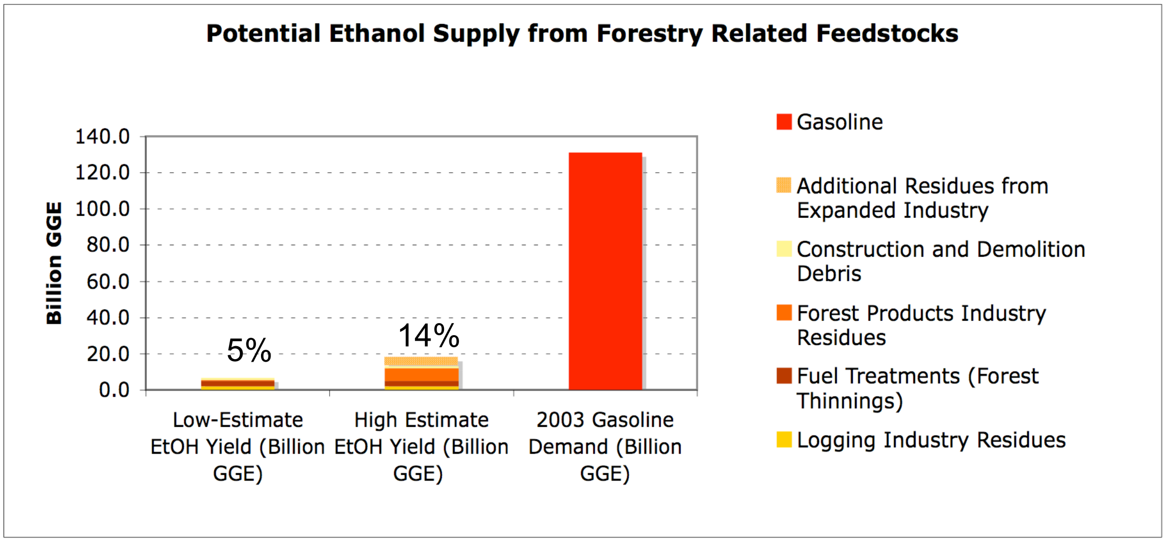
Table 5 Estimated Forestry Related Feedstocks

Between 130 and 320 million tons of forestry related feedstocks are available or might become available for biofuel conversion. The high estimate includes an estimate of additional residues from an expanded industry (see methods) and the low estimate excludes materials currently used for energy.

Material	High Estimate (Million Dry Mg)	Low Estimate (Million Dry Mg)
Logging Industry Residues	41	41
Fuel Treatments (Forest Thinnings)	60	60
Forest Products Industry Residues	116	8
Construction and Demolition Debris	20	20
Additional Residues from Expanded Industry	89	0
Total	**326**	**129**

Figure 6 Potential Ethanol Supply from Forestry Related Feedstocks

Between 5% and 14% of recent gasoline demand could technically be met by forestry related feedstocks. The higher estimate would require diversion of forest products industry residues, such as black liquor from their current use for industrial process energy. Furthermore, the high estimate includes an assumption that the entire forest products industry will expand due to economic and population growth.



Energy Crops and Crop Residues

Figure 7 shows the amount of transportation fuel produced in each of the scenarios that we modeled. The only scenarios in which enough fuel is produced to completely meet our current (2003) gasoline demand are the extreme scenarios in which all cropland is used to produce either corn ethanol or switchgrass for ethanol. In the more modest scenarios in which food security constraints are applied, between 25% and 76% of recent gasoline demand is met with biofuels. If all cropland were dedicated to either corn or switchgrass, 135% or 172% of recent gasoline demand could be met by biofuels, respectively.

The amount of fuel produced in a given scenario is determined by the parameters of the scenario (the energy crop considered and the land area suitable for energy crop production) as well as the interaction between the feed and fuel sectors which results from the food security optimization. Figure 8 shows the mix of livestock feeds produced in each scenario. As expected, a constant level of feed calories (expressed as million ton corn equivalents) is produced in those scenarios with food security constraints. In general, the baseline feed mix is shifted either towards more whole corn grain or toward corn ethanol coproducts (DGS) and away from roughage (hay) and soymeal. Because corn yields higher levels of feed energy per unit of land than other feed crops such as soybeans (see Figure 2), the optimization dynamics tend to produce more corn for feed in order to free up land for energy crop production (scenarios C1 and S1). This tendency is moderated by the production of corn ethanol coproducts, however, so much so that in some scenarios (C2 and C3) whole corn feed is reduced due to the abundance of DGS. It should be noted that large shifts toward corn production will be accompanied by increases in the externalities associated with corn production such as nitrogen runoff and soil degradation.

By reducing the need to grow whole corn grain for feed, the production of DGS permits the optimization procedure to grow corn for ethanol on a larger land area than switchgrass, which does not produce a feed coproduct. This explains why scenario C3 produces more transportation fuel than scenario S1, despite the fact that switchgrass produces more fuel per unit of land area. When the food security constraint is lifted (scenarios C4 and S2), switchgrass produces more fuel than corn ethanol. However, scenario S2 is associated with a severe deficit in feed, whereas in scenario C4 there is a glut of DGS.

Shifts in crop acreage associated with each scenario are presented in Figure 9. The largest shifts are generally away from low feed calorie yielding crops such as hay and soy and toward energy crops or corn for feed as discussed above. A small amount of wheat, cotton, and other crops are reduced in those scenarios, which permit energy crops to be grown on land currently used for exports. In scenarios C4 and S2, all cropland is dedicated to energy crops.

Figure 7 Gasoline Demand Met By Energy Crops by Scenario

In the presence of a food security constraint (scenarios C1, C2, C3, S1), biofuels from energy crops can supply between 25% and 76% of recent gasoline demand. If the constraint is lifted and all cropland is dedicated to biofuel production, between 135% and 172% of recent gasoline demand could be met with biofuels.

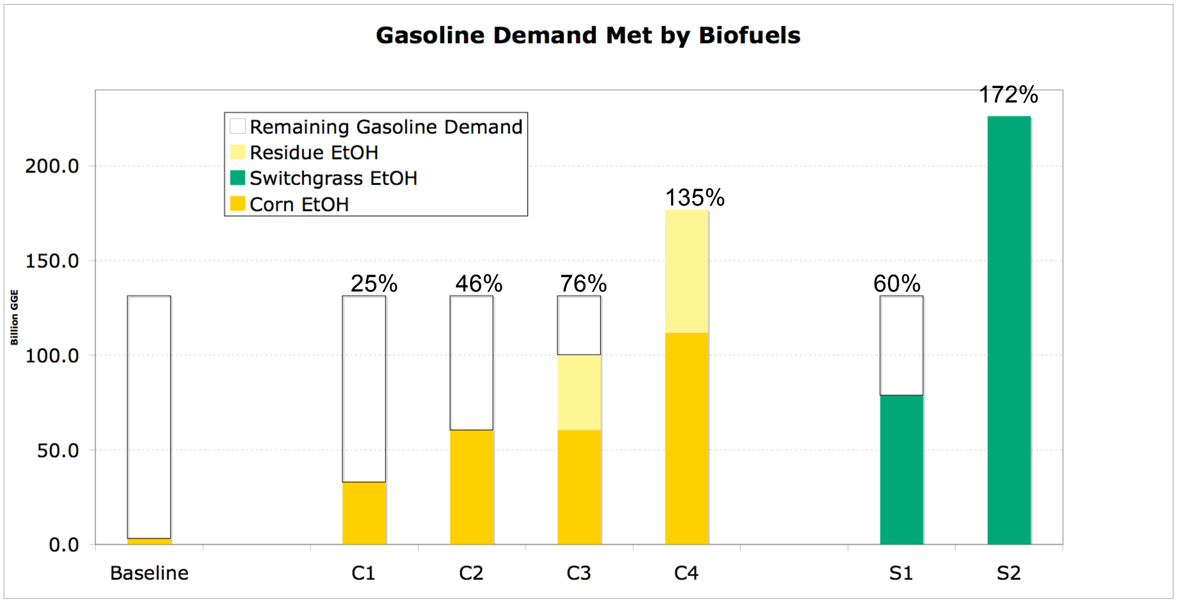


Figure 8 Feed Market Changes by Energy Crop Scenario

In the presence of a food security constraint (scenarios C1, C2, C3, S1), total feed calories (expressed in tons of corn equivalents) are held constant. In general roughage (hay), soymeal, and other feeds are replaced by either more whole corn grain or biofuel feed coproducts such as distillers grains. When all cropland is dedicated to corn ethanol production, there is a glut of distillers grains, whereas when all cropland is dedicated to switchgrass, there is an animal feed deficit.

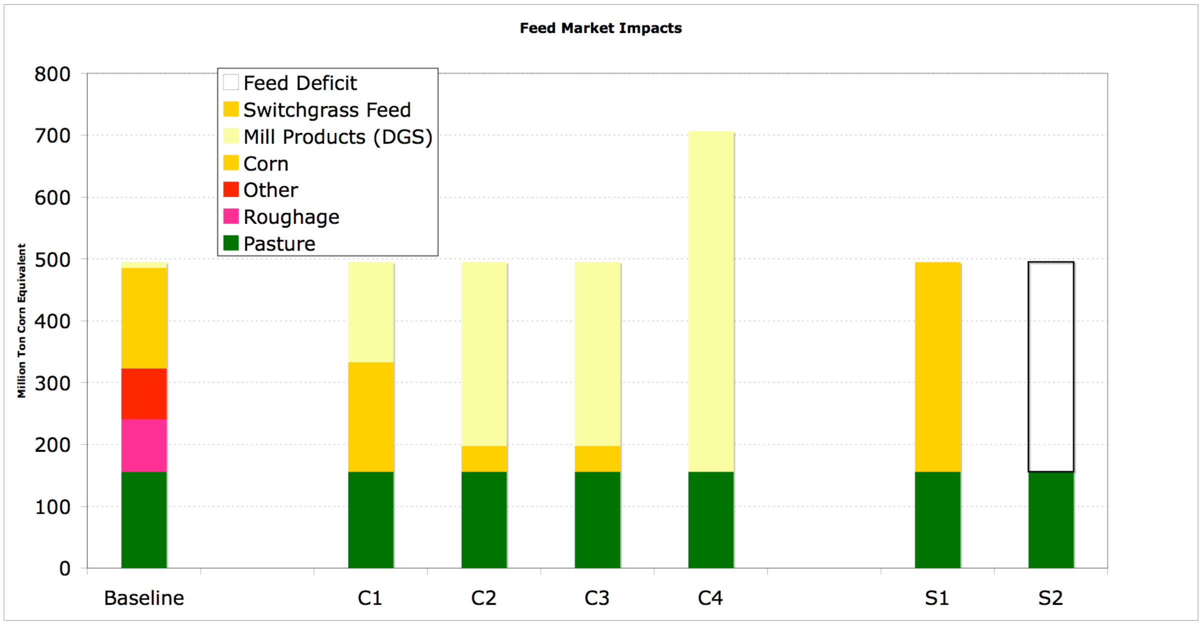
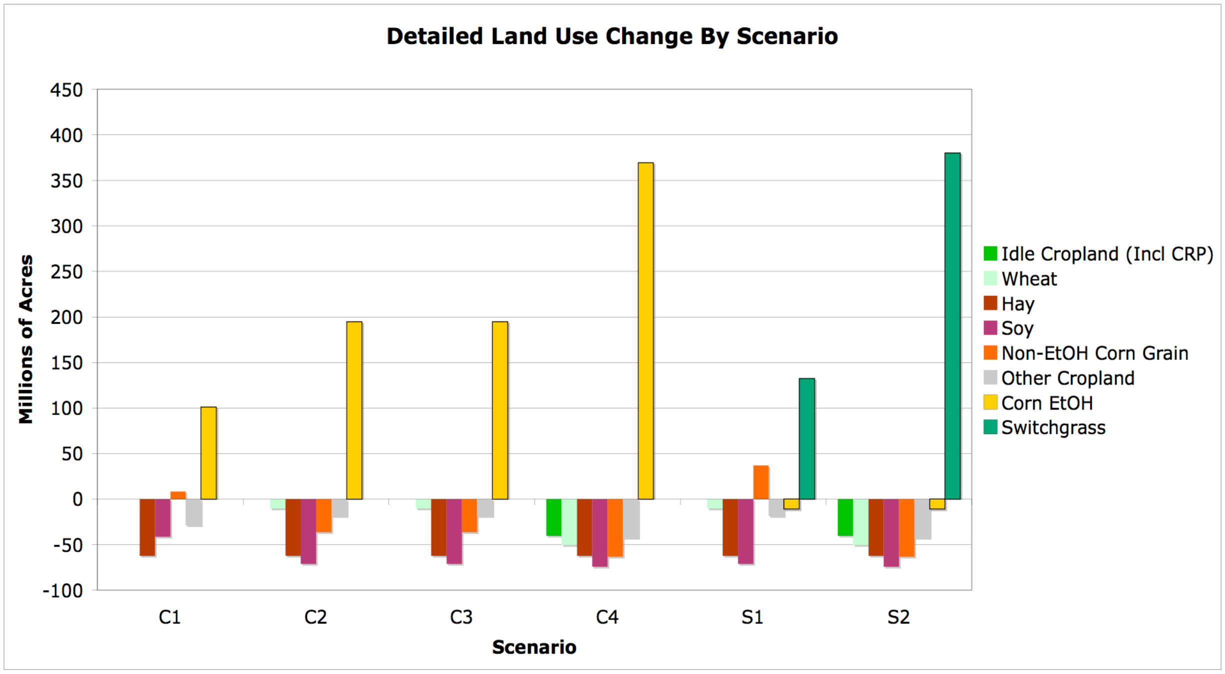


Figure 9 Detailed Land Use Change by Scenario

In the presence of a food security constraint (scenarios C1, C2, C3, S1), cropland tends to shift from the production of low-yielding feed crops such as hay and soybeans toward more whole corn for feed or biofuel crops. In scenarios C2 and C3, the high level of corn ethanol production eliminates the need for additional corn for grain due to the reduction of distillers grains. In scenarios C4 and S2, all cropland is shifted to corn ethanol and switchgrass production, respectively

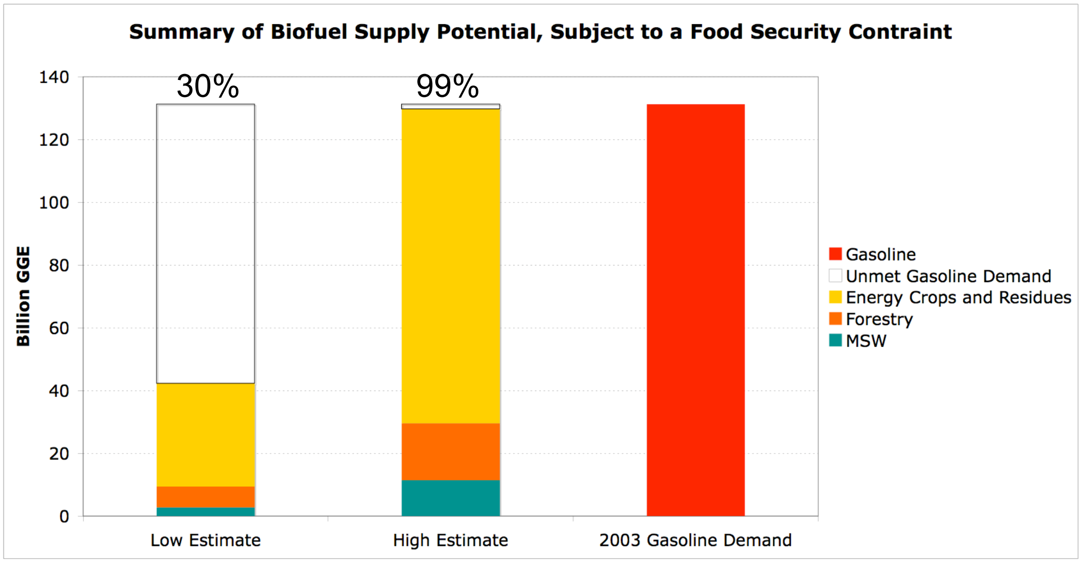


Summary

Subject to a simple food security constraint, we estimate that the technical potential of supplying transportation fuel using near-term conversion technologies is between 30% and 99% of 2003 gasoline demand (see Figure 10). Variation between the high and low estimate is based on uncertainty about feedstock supply rather than conversion technology yields, for which we use optimistic assumptions. While MSW and forestry residues can supply a modest amount of transportation fuel, the bulk of potential supply is from energy crops and crop residues. If the food security constraint is lifted, then the potential supply from all sources nearly doubles to 195% of 2003 gasoline supply. This value is based on a scenario in which all current cropland is used to grow high-yielding switchgrass for biofuels.

Figure 10 Summary of Biofuel Supply Potential Under a Food Security Constraint

Subject to a simple food security constraint, the technical potential of supplying transportation fuel using optimistic assumptions about near-term conversion technologies is between 30% and 99% of 2003 gasoline demand. Variation between the high and low estimate reflects uncertainty about feedstock supply rather than conversion technologies.



Discussion

In this study, we estimate the physical supply potential of liquid biofuels from domestic resources using near-term technologies. We estimate that nearly twice our current level of gasoline consumption could be met by biofuels if we were willing to forgo all other crop production. However, with a simple food security constraint, this value drops to 33%-99% of current gasoline consumption. Even these values reflect optimistic conversion yields and ignore cost constraints – both economically valued costs such as the cost of harvesting diffuse resources and external costs such as damage to ecological systems and human health. In particular, we did not explicitly model the climate impacts of the various biofuel pathways considered in this study. Limiting the analysis only to low-carbon biofuels may result in even lower supply estimates.

While several prominent studies have addressed the issue of domestic supply of biofuels relative to fossil energy consumption for transportation(7, 17, 18), ours is unique in that it explicitly models interactions between the feed and fuel system using an optimization procedure that adjusts cropland allocation among major crops. Our modeling shows that sizable increases in biofuel production need not result in decreased availability of animal feed, but *will* require changes in the composition of livestock diets away from hay and soymeal toward either whole corn or feed coproducts of biofuel processing such as DGS. In our model, these changes in feed composition are associated with land cover changes that favor more corn production. However, the possibility exists for new bioenergy crops such as switchgrass to produce feed coproducts as well(7), indicating that this result may be more general.

The manner in which we model the feed-fuel interaction as a constrained optimization problem is far cry from realistic. By fixing the level of food and feed consumption, we implicitly assume that diets will not shift as increased fuel production drives up the price of food and feed. We have also optimistically assumed that various feeds are perfectly substitutable on a digestible calorie basis. In such a world, the value of the corn ethanol coproduct outweighs the additional ethanol yield that switchgrass has compared to corn with stover collection. This is because the corn ethanol feed coproduct relaxes the constraint on feed production and permits more land area to be dedicated to fuel production.

Historically, transportation fuel demand has been rather unresponsive to price changes as well(5, 20), which we have not modeled. Thus, it is entirely possible for fuel markets to bid up the price of biofuel such that high-yielding switchgrass will be favored over corn ethanol, reducing the supply of animal feed. However, the degree to which this happens will depend upon the price of other substitutes for conventional petroleum and the price of petroleum itself. In theory, once agricultural markets are open to high levels of biofuel production, the relative ability of consumers to adjust levels of domestic food and fuel consumption (either by decreased total consumption, imports, or non-agricultural substitutes) will determine the level of food versus fuel production, with the least flexible commodity tending to dominate. In any case, we have demonstrated that it is technically feasible to maintain current levels of feed production while significantly increasing biofuel production. However, this is no guarantee that the price of feed and food products will not increase significantly. Food prices and the affordability of food are complex issues with many stakeholders including domestic consumers, overseas farmers, and food processors and retailers. Modestly higher food prices may be compensated for by dietary shifts away from grain-intensive meat consumption or reduced consumption of other goods. However, if food prices become too high, this may render our energy crop scenarios socially unacceptable. In such a case, policy interventions may be needed to help food and feed crops compete with bioenergy crops while maintaining reasonable food prices.

Waste resources are often overlooked in the discussion of biofuels. For instance, MSW is excluded from the USDA and DOE's Billion Ton Vision report (18), NRDC's Growing Energy report(7) and from paper's presented by biofuel skeptics (e.g. (17)). We found that MSW can probably play only a small role in supplying transportation fuel (2%-9%) of recent gasoline demand. However, these resources already have specialized collection and handling systems in place and may come at negative cost due to avoided landfill fees. Furthermore, the climate impacts (and other external impacts) of converting waste to fuel are likely low compared to crop-based biofuels. However, diverting wastes such as paper from the recycling stream may create pressure on primary resource extraction.

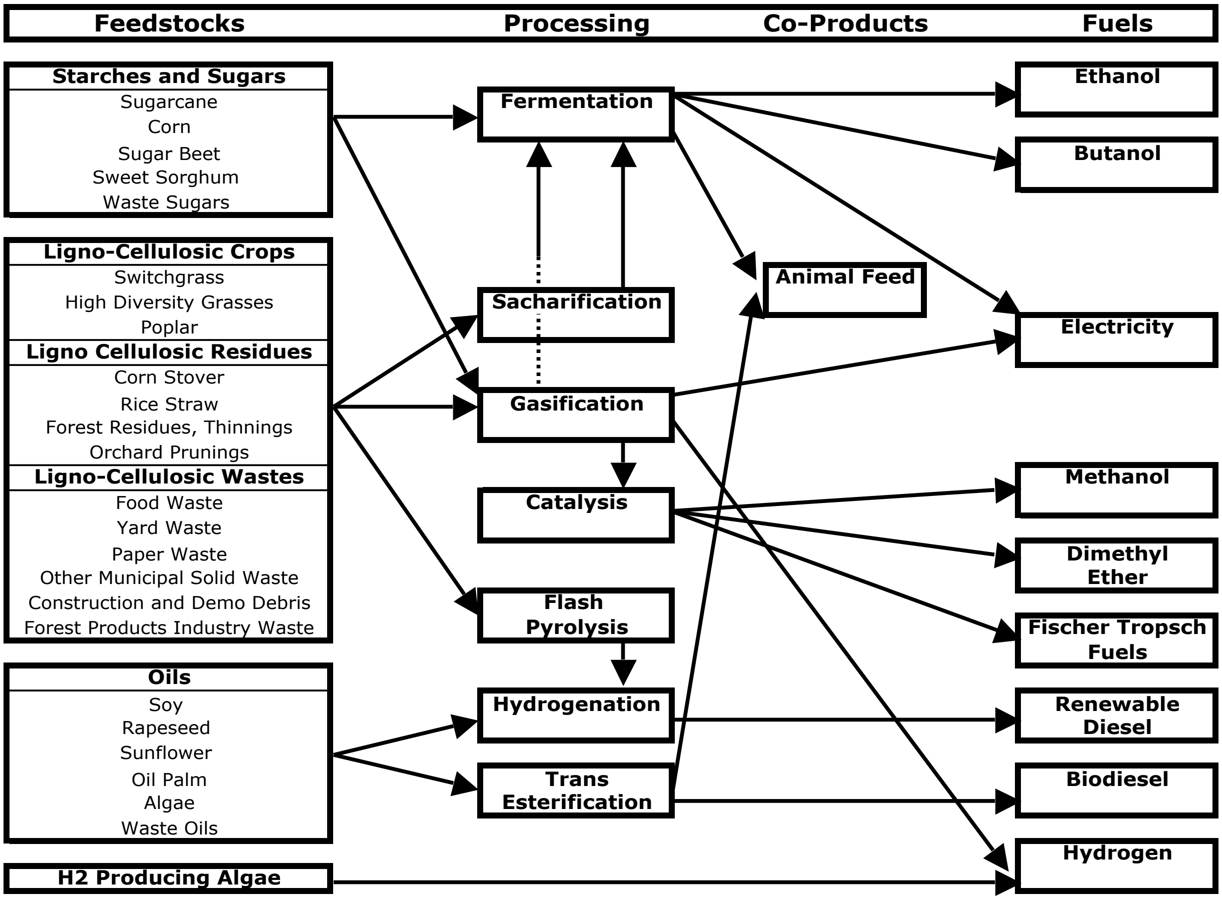
As with MSW, forestry residues offer a modestly sized, but potentially uncontroversial and low impact feedstock for biofuel production. The exception to this is logging residues, which do play an important role in maintaining soil health and wildlife habitat. Diverting forest products industry residues that are currently used for industrial process energy to liquid fuel production will require new sources of process energy, which may result in additional greenhouse gas emissions from fossil fuels. However, many more options exist for low greenhouse gas process heat (solar, nuclear, combined heat and power) than for low greenhouse gas liquid fuels. Thus liquid fuel production might be considered a more desirable use of such feedstocks.

We have shown that while domestic biofuels may play a significant role in replacing or supplementing conventional transportation fuels, they are by no means a "silver bullet" that can supply all of our needs. To replace all US gasoline consumption with biofuels, even under the most optimistic yield assumptions, it would be necessary to harvest all the source material in forestry residue and solid waste, eliminate agricultural exports, and either significantly shift animal feed diets toward whole corn and corn ethanol coproducts or eliminate some degree of domestic food and feed production. More realistically, biofuels should be thought of as one of several items in a portfolio of strategies for lowering the climate impact and increasing the security of our transportation system. Other strategies include smart growth, fuel efficiency, and plug-in vehicle technology. To ensure the climate mitigation benefits of biofuels, green labeling standards or a low-carbon fuel standard may be necessary. Research is needed to improve conversion technologies, agronomic practices, and feedstock handling in order to accommodate diffuse and heterogeneous feedstocks, lower costs, and minimize negative effects on climate, ecosystems, and human health

Appendix A - Biofuel Production Pathways

"Biofuels" describe transportation fuels derived primarily from (recently grown, as opposed to fossil) biological materials. There are several types of fuel that can be potentially produced from biomass, multiple processing strategies to convert biomass to these fuels, and an immense range of biomass feedstocks that could be utilized for one or more of these processes and fuels. Each unique feedstock, conversion, and fuel combination is referred to as a fuel "pathway." The net greenhouse gas emissions associated with a particular biofuel depends upon the entire fuel pathway, and can vary greatly even among pathways for which the final fuels produced are indistinguishable. Figure 11 provides an overview of selected biofuel production pathways that are discussed in more detail below.

Figure 11 Biofuel Production Pathways



Biofuel Feedstocks

Sugar and starch crops

Sugar crops, including sugarcane, sugar beets, and sweet sorghum, require relatively little processing to derive the simple sugar sucrose for fermentation to alcohol by yeasts. Starch crops such as corn, milo, or wheat require hydrolytic and enzymatic action to covert glucose and fructose to sucrose.

Ligno-Cellulosic crops

The cell walls of plants are composed mostly of lignin and cellulose. Cellulose is a polymer composed of starches that can be broken down into simpler components enzymatically through a process known as saccharification. Both lignin and cellulose release thermal energy when combusted for process heat, or when they undergo gasification or pyrolysis. Ligno-cellulosic crops, both herbaceous and woody plants, represent a potentially more widely available biofuel feedstock than sugar and starch crops Both herbaceous and woody crops are perennial, and where they replace annual crops they are likely to increase soil organic carbon, creating a carbon sink[6]. These crops may also have relatively low fertilizer and other input requirements, resulting in a relatively low GHG profile. Furthermore, because ligno-cellulosic conversion processes typically use the entire plant biomass either as direct feedstock or for process heat, the potential yields per land area are generally higher than for agricultural crops.

Ligno-Cellulosic Residues

Residues may be collected as a by-product of the production of other crops, such as corn stover or rice or wheat straw, or they may be collected after processing of other crops, such as lumber mill, cotton gin, or vegetable processing residues. Residues, especially corn stover, are expected to be the first feedstocks for cellulosic biofuels to be utilized. Excessive residue removal can have important non-greenhouse gas environmental effects, such as erosion, and so should be closely limited to a sustainable level. At any level, residue removal is likely to marginally increase crop fertilizer needs and decrease soil organic carbon loads, resulting in some greenhouse gas costs. Residues collected at processing sites, such as vegetable processing and milling wastes, do not increase agricultural GHG emissions.

Municipal Solid Waste

Municipal solid waste (MSW) destined for the landfill contains substantial ligno-cellulosic material that can be converted to biofuels. The organic fraction of MSW capable of serving as a biofuel feedstock (which does not include plastics or other energy-rich materials) constitutes 55% of all MSW destined for the landfill in California (Cascadia, 2004).

MSW, like industry residues, is already collected and concentrated, and so has a nearly-zero production “cost” and a low transportation cost.

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[6] Though, if perennial biomass feedstocks replace native ecosystems, there generally will be a net carbon emission, not a net sequestration.

Oils

Oilseed crops, including soybeans, canola and mustard seeds, and sunflower seeds, are grown throughout the United States. Palm oil is grown in tropical Southeast Asia and has been linked to deforestation and the draining of peat bogs, both activities that result in large net GHG releases. Some varieties of algae are known to produce large amounts of fatty acids and have been proposed as biofuel feedstocks.

Biofuel Conversion Processes

The primary biofuels produced at a commercial scale in the U.S. today are fermented corn ethanol and transesterified soybean biodiesel. Globally, fermented sugar cane ethanol is produced in large quantities as well. Ethanol can be produced via simple fermentation from other starch and sugar based feedstocks or from a wider range of cellulose based feedstocks through an enzymatic process known as saccharification that releases the starches in cellulose. Ethanol can also be produced from biomass-derived synthesis gas. Biodiesel can be produced from a range of oil-based feedstocks via the currently predominant trans-esterification process. Additional fuels in pilot- or small-scale applications include other alcohols (e.g. biobutanol and methanol), other diesel blendstocks (e.g. Fischer-Tropsch fuels, renewable diesel, and dimethyl ether), and gaseous biofuels (e.g. hydrogen and methane).

Fermentation

Alcohols are generally produced through fermentation. While fermentation of the simple sugars pressed from sugarcane, sweet sorghum, and sugar beets is simple, starch and cellulosic materials require increasingly complicated (and expensive) hydrolysis and saccharification processes before sugars are available to fermentation. Fermentation with different yeasts can produce either ethanol or butanol fuels.

Cellulosic material is often bound up with lignin in complex ways that must be broken before the cellulose is available for saccharification and fermentation. Thus ligno-cellulosic material must be pre-treated through one of several processes before enzymatic breakdown of cellulose can occur. Candidate pre-treatment processes include dilute-acid pretreatment and ammonia-fiber-explosion. The cost of pre-treatment is a major barrier to cellulosic alcohol production via the saccharification-fermentation pathway.

Transesterification

The reaction of biomass oils with alcohol in the presence of a catalyst produces esters and glycerin. The esters have similar properties to diesel, and glycerin is valuable coproduct.

Gasification

The partial combustion of biomass in an oxygen-limited environment can produce a CO- and H2-rich gas called synthesis gas that can in turn be used in several processes to produce heat, electricity, and liquid fuels. Synthesis gas can be reformed using the Fischer-Tropsch process to hydrocarbons, primarily middle distillates for diesel production but also some gasoline components. Synthesis gas can also be fermented to ethanol, or refined to a pure hydrogen fuel product.

Flash Pyrolysis

Pyrolysis is the first stage of the gasification process that, when optimized by a short residence time and zero-oxygen environment, produces in addition to combustible synthesis gas a heavy liquid hydrocarbon called bio-oil. Bio-oil can be refined to gasoline- and diesel-like hydrocarbons.

Hydrothermal liquefaction

Hydrothermal liquefaction uses high temperatures and pressure to combine water and biomass and convert both to an oily liquid that can then be separated to hydrocarbons and organic-rich water. The hydrocarbon components can then be added to standard petroleum feedstocks in refinery operations.

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